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UNITED STATES BUREAU OF MINES
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FACTORS AND CONDITIONS THAT AID IN ALINEMENT OF PILLAR EXTRACTION LINES IN COAL MINING

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FACTORS AND CONDITIONS THAT AID IN ALINEMENT OF PILLAR EXTRACTION LINES IN COAL MINING[1]

By J. N. Geyer[2]

IMPORTANCE OF PILLAR RECOVERY

During the early stages of the mining industry of the United States an apparently inexhaustible supply of high-quality, easily accessible coal made the product cheap and the attendant mining methods wasteful of recoverable coal. Because coal from advance places could be mined with less effort and a large output obtained as the entries advanced, much of the coal left in pillars to support the roof was lost. Squeezes often developed in these mined-over areas, or, if pillars were of sufficient size to prevent squeeze, the roof would be so weakened by long exposure that any pillar recovery was extremely hazardous.

As the value of unmined coal increased, a high recovery of the available coal became necessary. Numerous plans were tried during the period that followed, some of the methods proving successful while others were complete failures or only partly successful. As a better knowledge was gained of the roof strata and its behavior, however, pillar mining became more successful and methods suited to special roof conditions were developed.

In the study of falls of roof in bituminous-coal mines conducted by the Bureau, particular attention is necessarily directed toward the methods of mining used as they affect roof control in pillar extraction. As a result of these studies, several methods for winning the pillar coal and controlling the roof along rib lines under diverse natural and economic conditions have been observed, and it is believed that a brief discussion of these methods and their application will be of material aid in recovering the coal in other mines having similar conditions.

The data used in preparing this paper have been compiled from reports made in connection with the study of falls of roof and coal by Bureau engineers and includes coal mines in western Pennsylvania, northern West Virginia, and a part of southern West Virginia.

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DESCRIPTION OF THE DISTRICTS

In Pennsylvania the studies have been confined to mines in the Pittsburgh bed in Allegheny, Washington, Greene, Westmoreland, and Fayette Counties. Mines studied in West Virginia include those in the Pittsburgh bed in the Panhandle district; the Pittsburgh and Sewickley coals in the Fairmont district; and the Pocahontas No. 3 coal in McDowell County.

Topography

The topography ranges from gently rolling to broken in the Panhandle in West Virginia and the western portion of the field in Pennsylvania. In the eastern part of the field in Pennsylvania and in the Fairmont district in West Virginia the surface is more rugged, the streams having cut deep V-shaped valleys leaving comparatively sharp ridges. In McDowell County the surface is decidedly rugged.

Thickness of cover

The strata overlying the coal ranges from a few feet at outcrop to 1,000 feet in a few places. Covers of 500 feet are common over the Pittsburgh coal in the gas and coke region of Pennsylvania and in the Fairmont district of West Virginia. Over the Sewickley coal, where mined in West Virginia, the cover seldom exceeds 300 feet. In McDowell County, W. Va., the cover often exceeds 500 feet and as much as 1,000 feet has been encountered. The following table gives the range in cover over each group of mines studied:

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Cover or overburden on coals in the district studied

State and district	Cover, feet			Number of mines
	Minimum	Maximum	Average	
Pennsylvania:				
Pittsburgh bed -				
Allegheny and northwestern Washington Counties	Outcrop	500	165	8
North-central Washington County	25	800	295	8
Irwin, Greensburg, and Latrobe basins	Outcrop	550	265	12
Eastern Washington and Greene Counties	125	900	430	6
Fayette County	Outcrop	815	388	11
West Virginia:				
Pittsburgh bed -				
Panhandle	Outcrop	730	240	6
Harrison County	Outcrop	400	175	5
Marion and Monongalia Counties	Outcrop	900	390	9
Sewickley bed, Monongalia County	Outcrop	580	230	7
Pocahontas 3, McDowell County	Outcrop	1000	390	5

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Nature of Roof

The roof over the Pittsburgh and Sewickley beds is comprised largely of sandstone, limestone, shale, and clay. The sandstone strata vary from flaggy to massive structure and may occur in beds over 60 feet thick. Limestone beds may attain a thickness as great as the sandstone and be exceptionally strong, or they may be mixed with calcareous clays and have little strength. The shales vary widely in composition and strength.

In McDowell County, W. Va., the cover over the Pocahontas No. 3 coal is composed almost entirely of sandstones and sandy shales. Beds of massive sandstone over 100 feet thick are found. No calcareous rocks are found in the New River and Pocahontas groups of the Pottsville series, which formations are exposed above the Pocahontas coal in the mines studied. Typical stratigraphic sections of the roof are shown in Figure 1.

Coal Beds

The Pittsburgh coal varies from 52 to 108 inches in thickness and is characterized by its bright appearance, hard texture, and blocky fractures, the latter resulting from the pronounced face and butt cleats in the coal. It is of bituminous rank in the region discussed and varies from a steam and domestic quality fuel to an excellent coking coal for metallurgical uses.

The Sewickley coal lies approximately 100 feet above the Pittsburgh coal in the mines studied and ranges from 45 to 72 inches in thickness. In appearance the coal is similar to the Pittsburgh and is widely used for steam and domestic purposes.

The Pocahontas No. 3 coal, which is 55 to 98 inches thick in the mines studied, is of semibituminous rank, extremely friable, and has a columnar fracture; it is not characterized by well-defined cleats, as are the former coals. This coal is widely used in making metallurgical coke and for raising steam where low ash and high calorific values are required.

Floor

The material underlying the Pittsburgh coal varies from a hard limestone several feet thick to a fire clay that becomes soft and plastic when exposed to moisture.

The Sewickley coal rests on a stratum of hard fire clay, about 6 inches thick, below which is a sandy shale; in some instances the clay is replaced by a hard, sandy shale. The clay has a tendency to expand as the coal is removed in advance work, and in a few of the mines the bottom heaves badly in places that have stood for long periods.

Underlying the Pocahontas coal is a hard fire clay about 24 inches thick, sometimes replaced by a hard gray shale. The floor does not heave readily nor is it affected appreciably by water.

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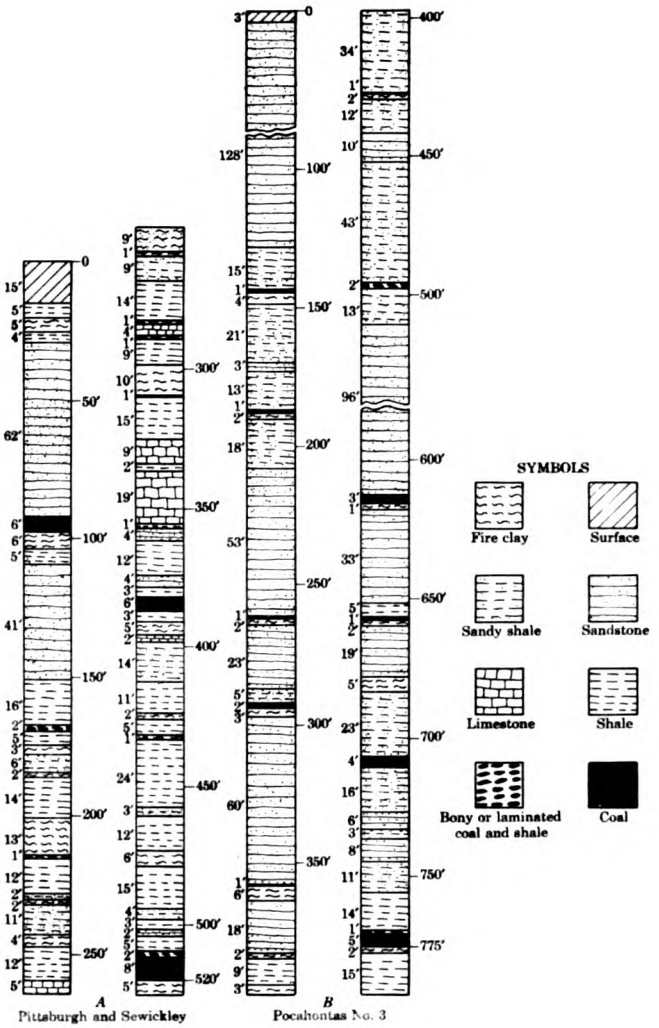

Figure 1 – Geologic section through strata overlying the Pittsburgh, Sewickley, and Pocahontas No. 3 coal beds.

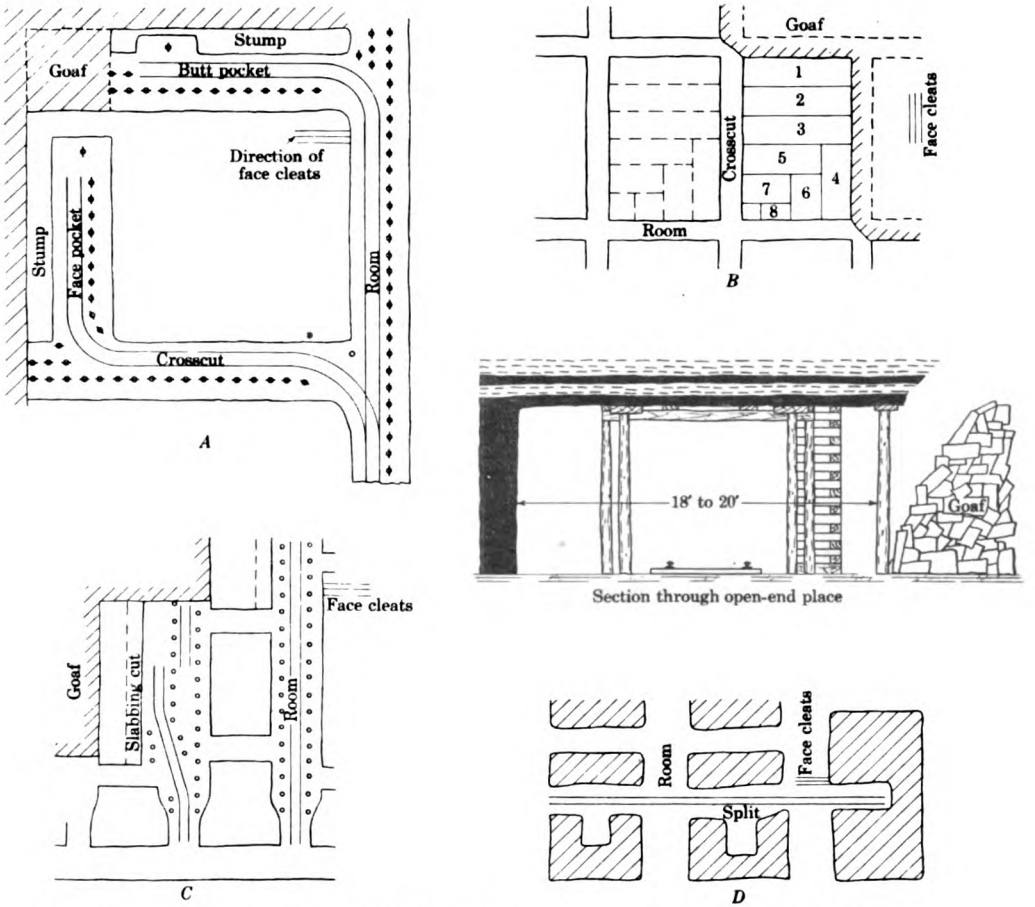

Figure 2 – General methods of extracting room pillars. A-Pocket and stump. B-Sequence of operations in open-end pillar mining. C-Slabbing. D-Splitting.

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Mining Methods

A detailed description of the methods of mining used would require separate treatment; however, any discussion of pillar recovery must of necessity be prefaced with a brief review of the methods used in developing the properties.

Some form of the room-and-pillar system was used in all of the mines studied. The types ranged from wide rooms and narrow pillars not recovered to the block system with narrow rooms and wide pillars which are systematically recovered. Rooms varied in width from 10 to 24 feet and room pillars from 9 to 11 feet. In general, where the rooms are wide the pillars are narrow; in a mine leaving 9-foot pillars the rooms are 21 feet wide.

The mines opened in the Pittsburgh coal and most of those in the Sewickley bed have been developed with the rooms driven on the face cleats in the coal - which means, that the face of the room is parallel to the face cleats in the coal. The room entries are driven parallel to the face cleats or on the butts and are turned off face-entry systems 600 to 2,400 feet apart. These face entries, together with main butt-entry systems, driven parallel to the room entries and connecting the face entries at intervals of 1,200 to 4,000 feet, divide the mine into panels. Headings in each entry system are driven on centers of 30 feet to 125 feet and 9 to 18 feet wide. Several of the mines using the room-and-pillar block system drive headings, rooms, and crosscuts the same width and on the same centers, generally 80 to 100 feet.

The cleat in the Pocahontas No. 3 coal is poorly defined and is not considered when developing a property; the dip and form of the property are controlling factors. Rooms in the mines visited were 16 to 25 feet wide, leaving pillars 40 to 50 feet wide. Headings generally are driven 12 to 18 feet wide, but in a few instances haulage headings have been driven 20 feet wide and air courses as much as 24 feet wide. Headings are on centers of 60 to 70 feet. The mines are generally laid out in panels similar to the mines in the Pittsburgh region unless the coal area is broken as the result of outcrops, in which case the practice has often been to make several entrances along the outcrop connected with an outside tramway.

The coal mined in development and a large portion of the pillar coal is mined with coal-cutting machines. In only one large mine was all of the coal hand-mined. Most of the coal is undercut on the floor with shortwall-type machines; in the other mines, some form of track-mounted mining machine is used, cutting either at the top or on the bottom. A few of the track-mounted machines employed are equipped for shearing, but this feature is not always used.

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Mechanical loading is used to a small extent, but in most instances is still in the experimental stage. Although this method generally has proved sufficiently successful, even in pillar recovery, to warrant serious consideration, its economic use often depends on a shortage of mine labor, and the decreased demand for coal during the past few years has not been conducive to widespread adoption of mechanical loading.

GENERAL CONSIDERATIONS IN RECOVERY OF PILLARS

Essentials to successful pillar mining are the removal of all standing coal along the goaf that might delay or prevent free roof subsidence and complete control of the roof weight along the break lines. With these facts in mind, there are several factors that should be considered carefully by the management of any coal mine before attempting to recover pillars and, if possible, before extensive development is done. The factors controlling pillar recovery may be grouped under three heads: (1) natural conditions, (2) economic factors, and (3) safety considerations.

Natural Conditions

The principal natural or physical conditions that affect coal mining are the cover overlying the coal, the coal bed worked, and the strata underlying the coal that may be affected by or itself affect the removal of the coal. The overlying strata or roof is considered in two parts: the immediate roof, or that part first above the coal which is not normally self-supporting except over limited areas, and the main roof which is comprised of that part of the overburden above the immediate roof and is considered self-supporting over the working places. As behavior of these in mining is different, it is necessary to discuss each individually.

Main Roof.- The main roof may affect mine development if the cover is heavy and a strong, massive rock stratum lies above a weaker stratum near the coal. In this event the massive formation acts downward more or less equally over a large area and if the pressure is sufficient will cause the weaker material to flow into the passageways opened in the coal bed. This condition generally exists only in entries driven into virgin coal and rarely, if ever, affects pillar recovery. The factors most to be considered in planning pillar extraction are the composition, structure, strength of the strata individually and collectively, and the weight of the overburden.

Coal deposits were laid down during periods of sedimentation and as a result the strata adjacent to the coal beds are sedimentary in origin except in some districts where local igneous intrusions have occurred. The rock strata most commonly associated with bituminous coal in Pennsylvania and West Virginia are sandstone, limestone, shale, and clay.

The sandstones, if of massive formation, may be difficult to break and have a tendency to bend so as to cause a squeeze, especially if any coal is left standing in the goaf, but those beds having weak structure break readily and are seldom difficult to control.

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The calcareous muds which formed limestones were often deposited at such depths that they were free from superficial currents and the interruptions that accompanied the deposition of shales and sandstones in the shallower water; as a result, the pure limestones are relatively thick-bedded and strong. Earthy limestones, which are frequently encountered in the areas studied, may be little stronger than a clay deposit or have a strength approaching that of a pure thick-bedded limestone. Thick strata of limestone may therefore be difficult to break and, if obstructions to complete subsidence are left in the goaf, the limestone may be supported sufficiently before the elastic limit is reached to prevent fracture and result in a squeeze. The muds forming shale were often deposited in shallow water within reach of swift or variable currents which, with frequent changes in the composition of the muds, produced marked stratification. As a result of stratification and jointing, the shales are generally broken without difficulty.

Clays encountered in the roof behave much like weak shales until exposed to moisture, after which they disintegrate rapidly; ordinarily they have little effect on mining unless they occur in the immediate roof or in the floor.

Immediate Roof.- The immediate roof is a factor in mining that must not be overlooked in both development work and pillar recovery. In general, the immediate roof strata must be supported until the pillars are withdrawn or taken down as the working places advance into solid coal as is true often with draw slate. The immediate roof generally consists of shales, clays, and coal and is seldom more than 10 feet thick. Clay, such as that forming the draw slate over the Pittsburgh coal, as a rule must be taken down as exposed unless the coal bed is thick enough to permit leaving a few inches of head coal to protect the clay from the mine atmosphere. If a stratum of coal several inches thick occurs in the immediate roof, it will often prevent weathering of weaker strata above, although its actual strength is not great.

In pillar work the behavior of the immediate roof depends, to a large degree, on the action of the main roof. If the main roof breaks close to the rib line and does not cause appreciable bending over the pillars, little trouble need be expected from the immediate roof. Another important factor is the time interval between exposing the roof in rooms and the subsequent pillar extraction; the longer this interval the more weakened becomes the immediate roof, with increased hazard and expense when the pillars are ultimately extracted.

Coal bed.- The thickness of the coal bed, the structure of the coal, and its strength are important factors in the recovery of pillars. The thickness of the coal is of importance in determining whether or not pillars can be recovered. If the lowest member or members of the main roof are of massive formation and bend appreciably before rupture, it is possible in mining thin beds for the roof to rest on the floor before the elastic limit is reached, resulting in an unavoidable squeeze. Under such conditions, some form of longwall mining might be advisable.

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Most bituminous and some semibituminous coals have vertical joints or cleavage planes along which the coal, in developed areas, tends to open when under heavy roof loads. Coals with poorly defined joints generally have greater rigidity than coals with well-defined cleats. The effect of structure on the strength of coal in pillars is discussed more fully in another part of this paper.

The strength of the coal in pillars is of great importance if the pillars are to be mined, and an early attempt should be made by the management of each mine to determine the amount of coal that must be left in pillars along the rib line in order to break the roof and prevent its weight from riding over the pillars.

Floor.- The floor may or may not be a factor of consequence in pillar recovery. If the floor heaves to such an extent that grading must be done to maintain the track in serviceable condition, the removal of pillars may be delayed at some points along the pillar line, introducing irregularities in the breakline. Occasionally, a floor material that flows readily under the roof weight may cause narrow pillar stumps to overturn partly, making extraction difficult and hazardous.

Economic Factors

Pillar extraction is not always economically practicable. Some of the more important factors to be considered are the value of the coal in place as compared with the value of the surface which might be damaged by subsidence, the value realized from the coal against the cost of recovery, and the possibility of water's entering the mine through surface breaks or from water-bearing strata overlying the coal. These factors should be considered carefully before extensive development is done, as changes made after a property has been largely developed are seldom entirely satisfactory. An additional factor that must be considered in mines where a large number of rooms have already been developed is the cost of reconditioning the places for pillar recovery. This will vary depending on the behavior of the roof and floor and the length of time since the rooms were developed. The principal items of expense are relaying track, retimbering, and removing falls.

In a region where the surface is valuable and subsidence would cause damage greater than the value of the coal would justify, pillar mining could not be considered. Where the coal is extremely valuable, as in the Pennsylvania anthracite region, the open area resulting from the removal of coal may be filled with sand or other waste material to prevent destructive subsidence and allow maximum recovery.

If a heavy draw slate overlies the coal and must be taken down in all working places, the cost of handling this rock in pillar work may be as much as the profit realized from the sale of the coal. In this case, however, pillars may possibly be mined profitably during periods of coal shortage, although intermittent pillar mining is not generally successful.

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Where the coal is under cover of less than 100 feet, there is always danger of large inflows of surface water during rainy seasons if the roof is broken. This has caused the abandonment of pillar recovery in some mines where other conditions were favorable to pillar mining.

In certain localities large quantities of water are contained in the roof strata, which, if broken, would allow much of this water to find its way into the mine. If a thick bed of clay lies between the coal bed and water-bearing formation, the water may be sealed off by the flow of clay into the break, but, as additional roof breaks are made, water will again enter the mine, making a continual problem. In farming regions, to break a water-bearing formation often drains the wells in the district and brings damage suits or injunctions against the mining company.

Where rooms are driven as the entries are advanced and pillar extraction is delayed, the cost of recovering the pillars increases until in some instances the cost makes recovery prohibitive. This is especially true if heavy falls have occurred in the rooms and the pillars are too narrow to admit of driving a split parallel to the room to reach the back of the pillar.

Safety Considerations

The relative safety of a method of mining is sometimes overlooked until a series of accidents has forcibly focused attention on the hazard. This is particularly true in some forms of pillar recovery where the workmen are required to work under roof heavily stressed or where large open areas exist along the break line.

The greatest hazards to the workmen in pillar mining are falls of roof and coal from the sides. These may be minimized, first, by choosing a method of pillar recovery that most nearly controls the roof stresses incident to breaking the roof and prevents the carrying of excessive weight by the pillars; second, by an effective system of timbering that affords ample protection from falls of the immediate roof and spalling coal from the sides; and third, ample supervision by competent officials, without which no system of mining or timbering will be effective.

METHODS OF EXTRACTING PILLARS

The common methods of extracting pillars in the districts studied are (1) the pocket-and-stump; (2) open end; (3) slabbing; and (4) splitting. The pocket-and-stump method is the most generally used of the four and the open-end method is second in favor. The slabbing and splitting methods are seldom used in systematic recovery unless in conjunction with some other method.

The pocket-and-stump and open-end methods are similar in general principle, the greatest difference being in the method of supporting the roof along the rib line. In the former method a narrow pillar of coal known as

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the stump is left along the goaf to support the roof while driving the pocket (see fig. 2A); with the open-end method, however, the pocket is open on the goaf side and the roof is supported on timber as in Figure 2 B. When the pocket-and-stump method is used, it will be noted that the workman's retreat is always protected by coal even during removal of the stump, but in the open-end method the roof on the goaf side is carried on timber which must be removed after the coal has been mined across the end. A choice between these two methods depends, to a certain extent, on the behavior of the roof and character of the coal, neither of which has been studied sufficiently for the formulation of rigid rules; however, such observations as have been made will be discussed under the behavior of pillars along the rib line.

An example of the slabbing method for the recovery of pillars is shown in Figure 2 C. By this method successive slabs are cut from one rib after a room is finished, until as much of the pillar is removed as can be recovered safely. The disadvantage of this system is that the open area of the working place is always increasing and that the loaders are always working away from the solid pillars toward the goaf.

Figure 2 D shows a method of recovering pillar coal that is now seldom found, although its use was common in the early periods of mining. By this method a room is driven through the pillars, splitting them into smaller blocks; from this secondary room, pockets are turned at right angles and driven into the small pillars to recover such coal as may be mined safely. This method amounts to little more than gouging the pillars, and as the recovery is seldom high, the method is wasteful and generally results in a squeeze.

DESCRIPTION OF RIB LINES

In pillar recovery it is essential to relieve the pillars being mined of all possible weight in excess of that resulting from the cover directly over them. The ideal method would be to cause the roof to shear vertically along the pillars as the coal is removed, but as this would be extremely difficult to accomplish in practice, the solution lies in extracting the pillars in a manner that will produce breaks most closely approaching the ideal and at the same time will produce the least stress in the roof over the working places.

In advance mining and during the early stages of pillar extraction the roof behaves like successive beams, but as the unsupported span becomes greater the lower members of the roof break and fall. The removal of additional pillars again increases the open area and the lower strata of the roof are stressed like cantilever beams and will fall as the weight of the overhanging strata becomes sufficient to break the rock. Similarly, as the span is increased, the higher strata fall until the surface is reached and the entire roof may be considered a series of cantilevers. In a cantilever the bending moments and shear stresses are maximum at the point of support and, if these stresses are to be utilized fully to break the roof, the points of support

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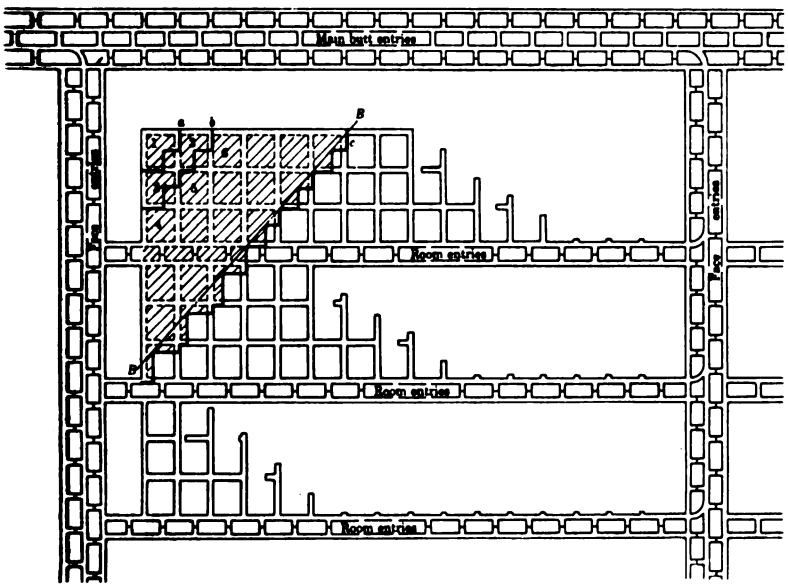

Figure 3.-Development of a single rib line.

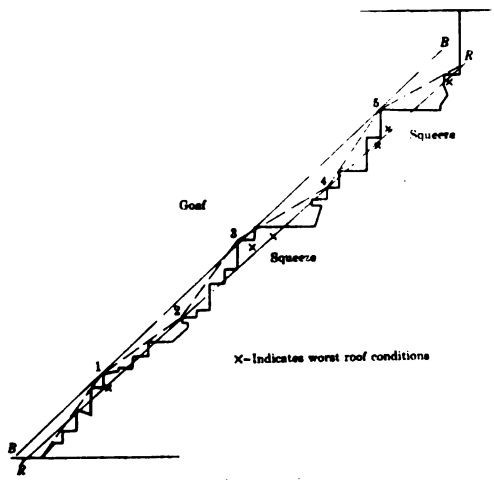

Figure 4.-Trace of irregular rib line, showing effect on roof over pillars.

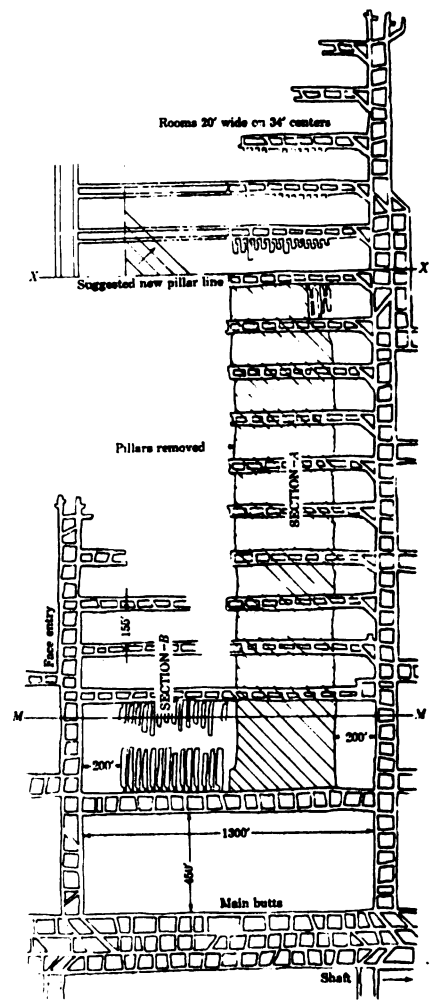

Figure 5.-Mining pillars in narrow panels with suggested method for improvement.

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should lie along a straight line. As a result, pillars are generally extracted along continuous lines of varying lengths, the traces of which resemble a series of steps as shown in Figure 3. In the strictest sense, such a rib line could hardly be considered a straight line; however, the actual trace of the line is not as important as the points supporting the overhanging roof. Along such a line the roof strata, except the weaker members of the immediate roof, are supported as beams across the goaf area between the pillars; but the main roof overhanging the goaf as a cantilever is most heavily stressed at the points of support or along the straight line B-B through the corners of the pillars extending into the goaf.

The more common forms of rib lines are the single line, the compound line, the diverging V-line, and the converging V-line; of these, the single line is the most common and represents the rib line in its simplest form.

The Single Line

A single line generally is commenced by removing a pillar at one corner of a panel, like pillar 1 in Figure 3. When the extracted area reaches line a, mining is commenced in pillars 2 and 3, to be followed by the extraction of pillars 4, 5, and 6 when the goaf area extends to b.

After establishing a rib line, it is essential that the break line be kept straight. By this it is not meant that a corner of each pillar must at all times coincide with the break line, for such a condition would be difficult to maintain in practice, but it is necessary to have a sufficient number of the pillars to coincide with this line to support the roof and to distribute this support uniformly along the entire rib line, because if the load is supported unequally, the roof will crush the overloaded pillars and develop into a squeeze.

The effect of an irregular rib line is shown in Figure 4. This rib line is approximately 2,400 feet long and under heavy sandstone and sandy shale cover. It will be noted that at points 1, 3, and 5 the pillars coincide with line B-B, which should be the break line if the pillars are to be relieved of excessive roof weight. However, as these points are approximately 750 feet apart and the cover is 500 to 700 feet thick, the load is too great for the coal to support, causing the pillars at these points to crush and breaking the roof over the working places. If the cover were light and the rock structurally weak, a series of short break lines connecting points 1 to 5 with the ends of the rib lines might prove reasonably satisfactory, but a strong roof strata will act along a straight line over the pillars, the exact position of which will be determined by the strength of the supporting pillars and the weight of the overlying strata. It will be assumed that this line lies along R-R; then on the goaf side of this line the pillars will be crushed appreciably and the roof over working places will show signs of failure. An examination of the working places along this line disclosed that the pillars at points 1, 3, and 5 were badly crushed, rendering recovery hazardous and

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expensive, and that the roof over working places was broken and often fell. The points where the squeeze was most apparent on the pillars and roof are designated by crosses (X) on the diagram.

Opinions differ as to the most satisfactory length for rib lines and, in the mines used as a basis for this report, rib lines less than 500 feet and up to 4,000 feet long were being maintained. The principal factors determining the length of rib lines are the strength and thickness of the roof, control of ventilation, and the production requirements. Only the first of these has any direct bearing on the control of the roof; the second is purely a safety measure and depends on the size of panel that can be ventilated safely by a separate split of air; the third factor, depending on production requirements, becomes important if the output demands fluctuate widely, in which case short lines may be more satisfactory.

Careful consideration should be given in planning pillar extraction to provide rib lines of sufficient length to prevent strong roof strata from spanning the open area across the panel or section from which pillars are being extracted. An instance illustrative of this was found in a mine operating in the Pittsburgh bed, a section of which is reproduced in Figure 5.

The main roof over this mine consists of limestone, shale, and clay; the limestone comprises 60 per cent of the cover, some beds of which are difficult to break. Referring to Figure 5, it will be noted that the total distance between face entries is 1,300 feet, of which 400 feet is reserved in barrier pillars 200 feet wide along each face entry. This leaves 900 feet in which to drive rooms and extract pillars; however, instead of driving rooms entirely across this distance as a single panel, the policy has been to turn rooms and recover pillars in only half of the panel, or across section A, having a span of only 450 feet. The lower roof strata breaks readily and falls are made as the pillars are removed, but no surface breaks have been found nor other evidence that would indicate subsidence of the main roof over this section. It is therefore evident that some stratum or group of strata in the main roof can not be broken across a span of only 450 feet. This conclusion was further substantiated when a squeeze developed over section B as rooms were turned near section A. Had the roof broken to the surface over section A, the pillars in section B would have been supporting only the roof over that section, and as the pillars were extracted, the roof would have continued to break and relieve the remaining pillars. A section through the roof at M-M showing the possible behavior of the roof is given in Figure 6. It is believed that subsidence is arrested at the limestone, a short distance above the Sewickley bed. This limestone is exceptionally strong and frequently occurs as a single bed 30 to 40 feet thick.

Assuming that the roof over section A behaves as shown, the unbroken strata will be supported equally by the coal on each side of the mined area. As the rooms are driven in section B, approximately 60 per cent of the support is removed along one side of the goaf and the roof commences to bend

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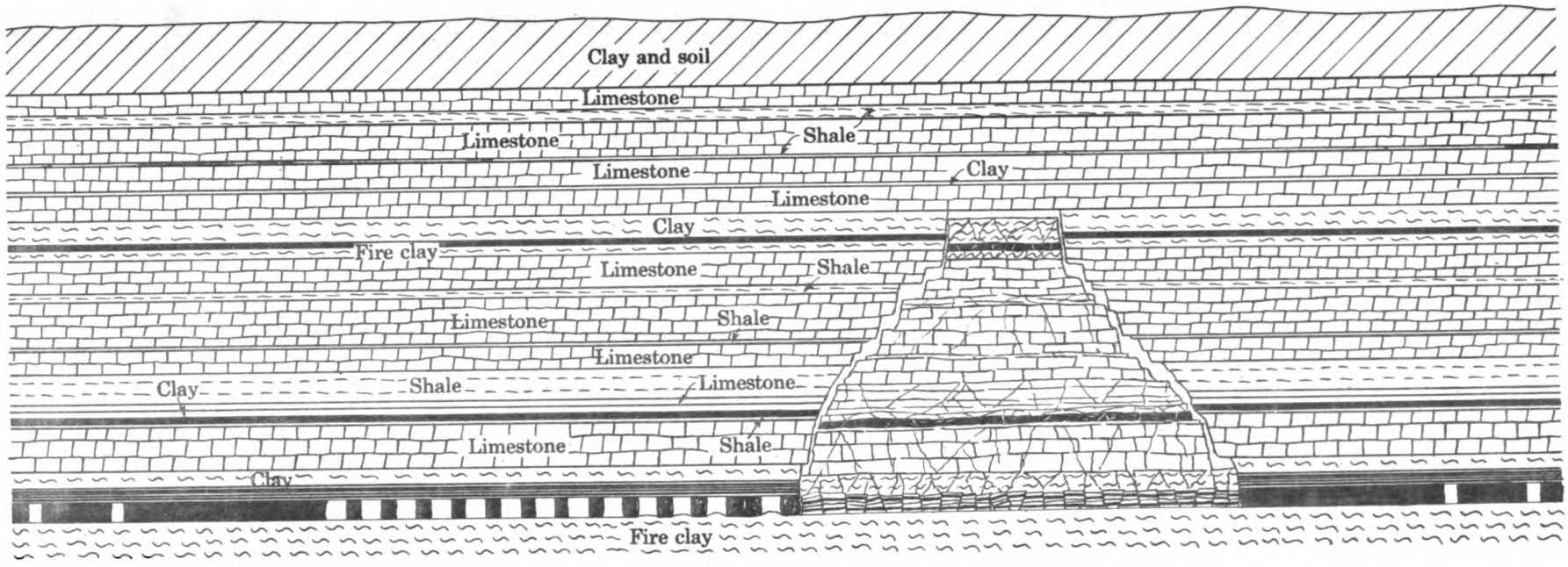

Figure 6.-Section through M-M, Figure 5, showing probable behavior of the roof.

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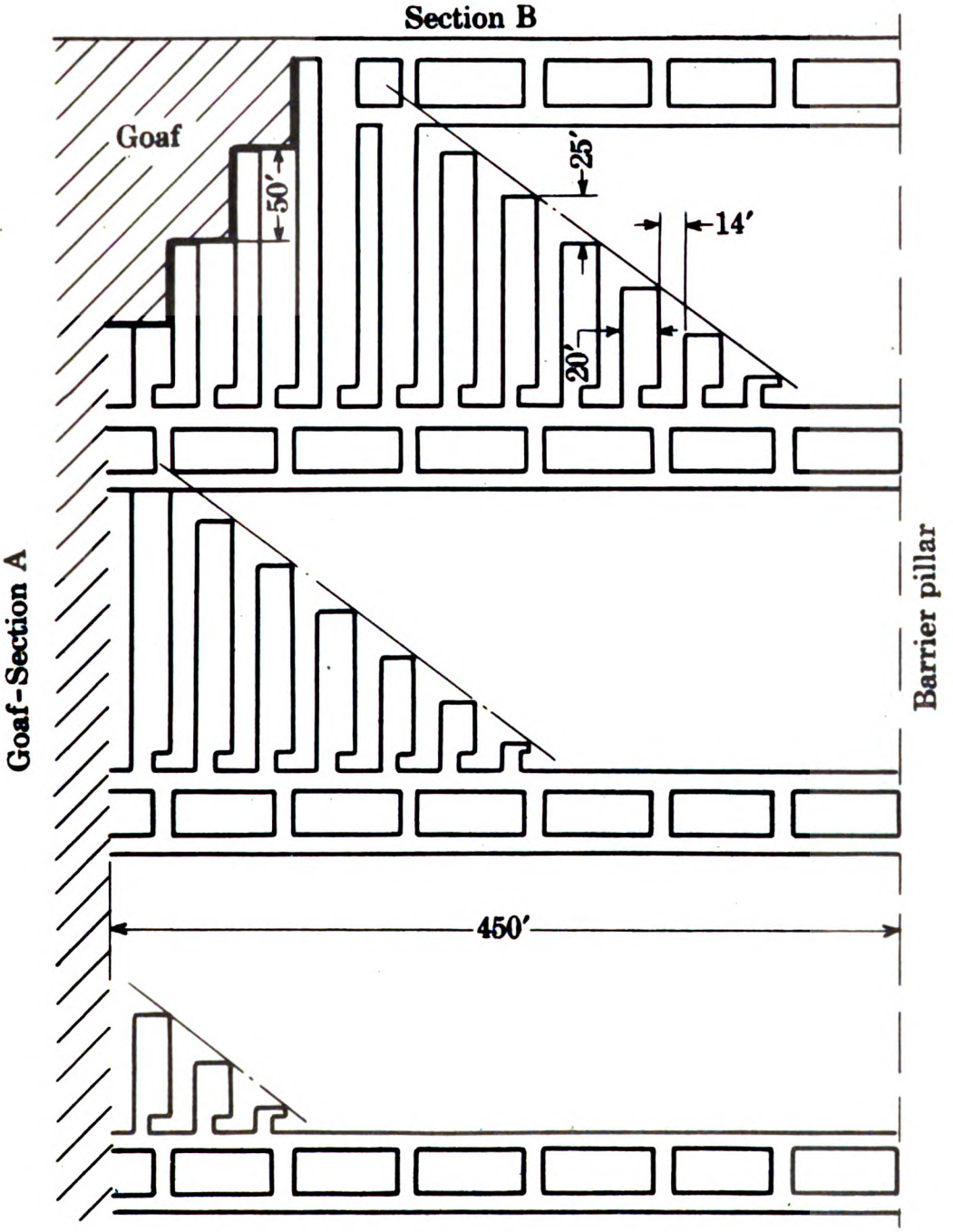

Figure 7 :-Proposed method of mining section B.

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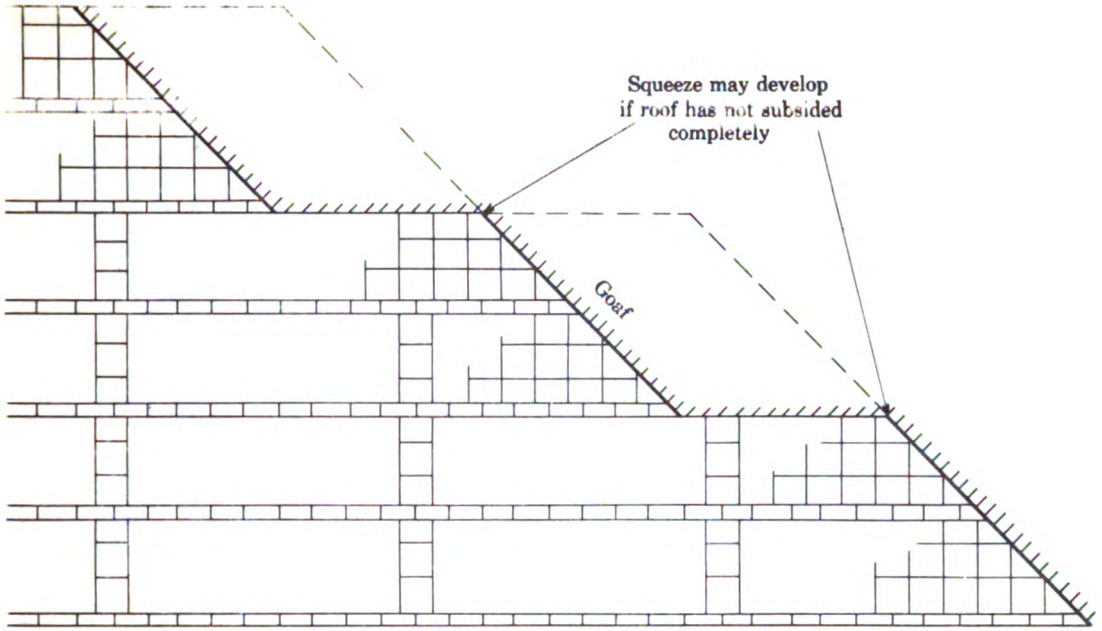

Figure 8 - General form of compound rib line.

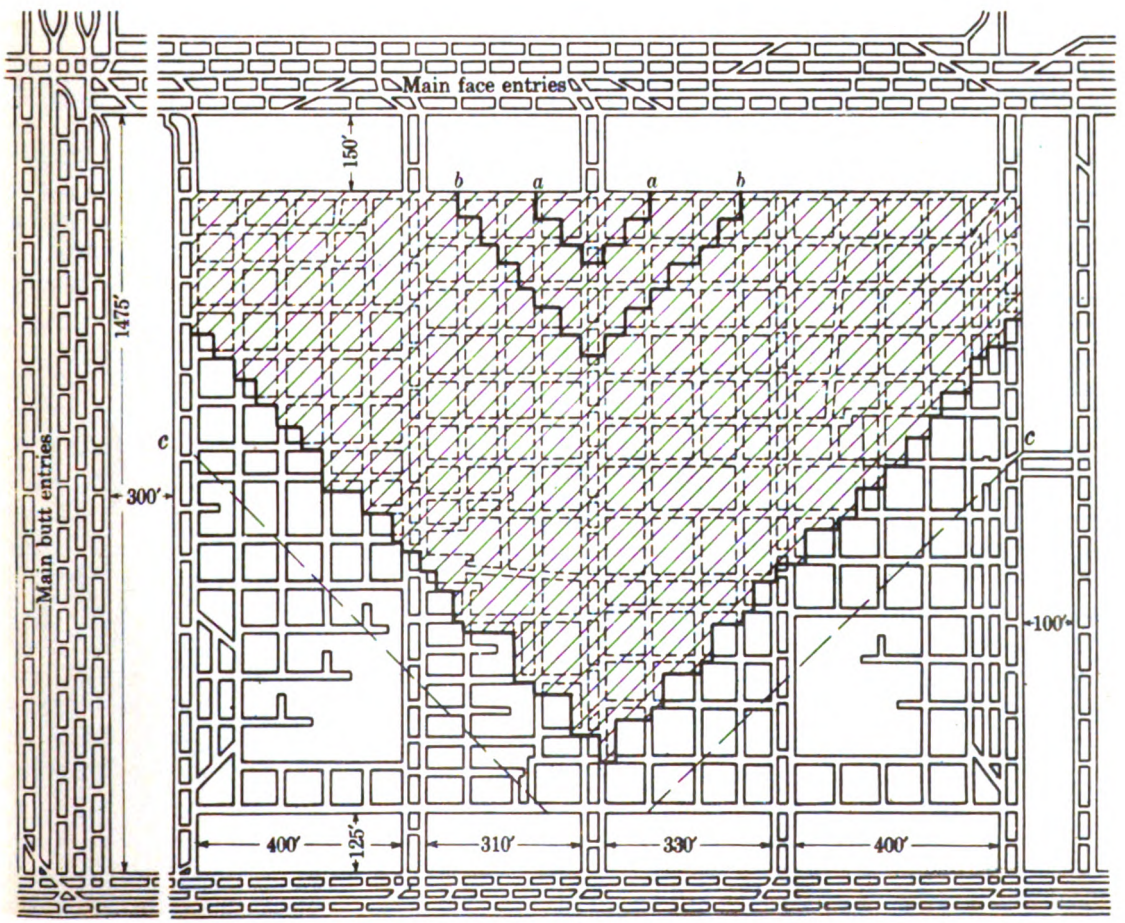

Figure 9 - Diverging V-lines.

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and crush the pillars. The squeeze may be arrested by leaving a barrier pillar between sections A and B strong enough to hold the roof, but this would necessitate the loss of coal left in the pillar and might cause further loss due to falls of the immediate roof. Instead of merely arresting the squeeze and getting such coal as might be recovered safety after leaving a barrier pillar, a method should be adopted that would admit of the recovery of all coal and also break the roof, relieving excess weight from the pillars. A plan such as that illustrated in Figure 7 should prove satisfactory for this purpose, although certain modifications in the width of pillars might be necessary; however, this can only be determined by trial. After this pillar line is established, pillar extraction should be stopped in section A until the pillars in section B have reached the line X-X in Figure 5, when a new rib line should be started as indicated, continuing across the entire panel.

The Compound Line

The compound line may best be described as a series of two or more parallel single lines, separated by offsets along which the roof may be broken. A typical line of this type is shown in Figure 8. Such lines are frequently developed from a long single line when production must be curtailed, and it is considered advisable to stop part of the rib line and work the remainder more or less regularly rather than attempt to maintain the entire line during intermittent operation. Under such a plan as much of the upper portion of the line as can be worked is continued, while the lower portion is stopped temporarily. When increased production is again required, the lower portion is started, but an offset now exists in the break line which may be allowed to remain, or, if not too great, may be removed by speeding up the recovery in the lower portion. When mining under a strong roof, a squeeze sometimes develops at the offset if the lower line is started before the roof along the offset is broken. If it is planned to maintain the broken line the distance along the offset should be sufficient to allow the roof along the offset to subside and reach a state approaching equilibrium where it joins the goaf of the line following. This distance will depend on the time required for subsidence, and the rate at which the rib lines advance. If the cover is not more than 200 feet and no strata difficult to break are encountered, subsidence may be practically complete in one year; but as a rule in the districts discussed in this paper, from 2 to 3 years are required for subsidence before pillars can be mined satisfactorily against a goaf; therefore the length of offset should be two or three times the distance that the rib lines retreat annually. Compound lines are advantageous when production must be curtailed and are less difficult to maintain in perfect alinement when two or more rib bosses are required along a single line, but there is always a possibility of squeeze over the pillars adjoining the goaf of the preceding line if subsidence is still active.

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Diverging V-lines

Diverging lines consist of two single lines that intersect to form an angle of less than 180°, the lines taking the general form of the letter V with the goaf lying within the angle, as in Figure 9. This type of line is used frequently to obtain a large production quickly and is started by removing the pillars at the midpoint along one side of a panel until a triangular goaf is formed with its base adjoining the solid coal and the other sides forming the rib lines, as in Figure 9, lines a and b, showing successive stages of development. It will be noted, therefore, that the pillars may be extracted from a given panel in much less time by using this system than by using a single line. This system will generally prove satisfactory where the roof is easily broken, but if massive strata, self-supporting across wide spans, are encountered in the roof and the pillars are being extracted slowly, some weight may be encountered at the vertex, although it is not likely that a serious squeeze would develop with this method. When the vertex reaches the boundary of the panel, the goaf distance across the point increases until two single lines are formed.

Converging V-lines

Converging pillar lines are formed by reversing the procedure used in developing the diverging lines. As shown in Figure 10, two rib lines are commenced at the extremities of one side of a panel, as represented by a and b which move toward each other and finally intersect to form the V-shaped line c, with the pillars to be extracted lying within the angle. The two break lines common to all V-shaped rib lines lie along the outer edges of the V and intersect at a point over the goaf beyond the last pillar. Figure 11 A shows the trace of a converging rib line where B and D represent the break lines theoretically intersecting at C; however, in practice the roof, unless structurally weak, seldom breaks in this manner at the vertex. The behavior of the roof over the intersection can be illustrated by placing a piece of cardboard, 8 to 10 inches square, over one corner of a table and allowing about one third to extend over the edge, as in Figure 11, B; then, while pressing the cardboard firmly against the top of the table, bend the projecting cardboard along both edges of the table simultaneously. As this is done it will be observed that the cardboard bends readily near the extremities but, as the corner is approached, it bends less freely until the conflicting stresses from the two sides become so great that the normal bending action ceases. This experiment demonstrates the reactions that occur in any strong formation in the roof, and in a roof comprised of several such strata the stresses probably would be even more complex. As a rule these conflicting stresses prevent clean breaks as the coal is removed and increase the load carried by the strata; as a result, the pillars are crushed and unless the cover is light the weight develops a secondary break line across the vertex, as shown by E-E. The position of this line depends on the roof weight at the vertex and the strength of the pillars, and generally lies approximately 100 feet back of the vertex; but the stressed zone, as indicated by crushed pillars and broken immediate roof, may extend back over 300 feet from the point.

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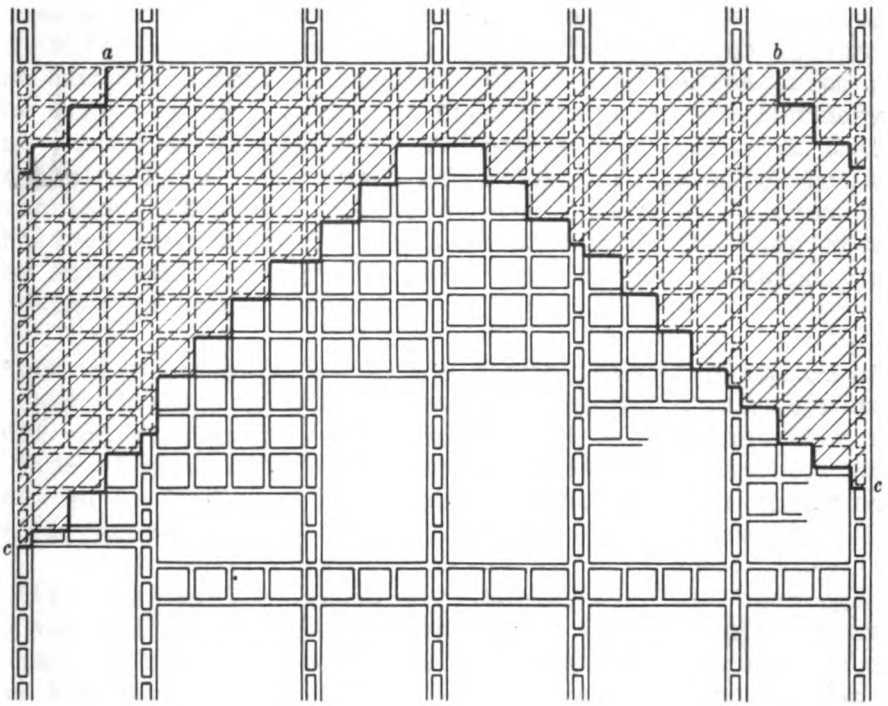

Figure 10.—Converging V-lines.

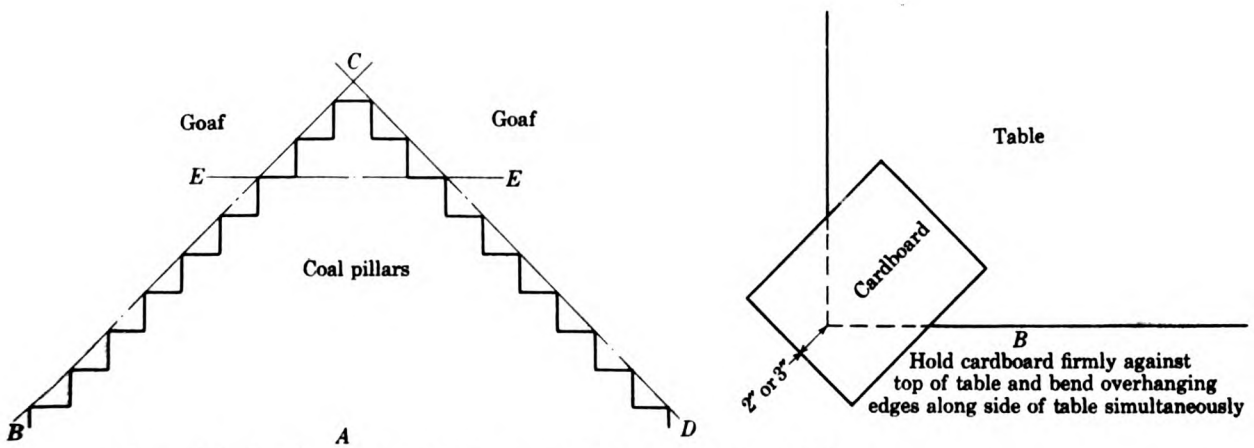

Figure 11.—Roof stresses developed along converging rib lines.
A, Trace of converging-type rib lines showing break line;
B, Experiment illustrating behavior of the roof over converging V-lines.

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Conflicting Break Lines

In mines where several rib lines are maintained there is a possibility that the stresses produced along one break line will meet those set up by another line, which may, if the stresses are of sufficient intensity, cause breaks in the immediate roof at points several hundred feet from either pillar line. In one mine the roof over developed rooms near one boundary line was broken as the result of stresses set up between a rib line in that mine and one in an adjoining mine. The two break lines were parallel but traveling in opposite directions. The roof over the rooms commenced to break when the opposing rib lines were about 900 feet apart, but at the time of visiting the mines the interval was only 200 feet, and the roof, a strong shale, was broken to a height of about 3 feet.

In another mine heavy falls were occurring over a distance of about 400 feet on the four headings of a main entry system which had been driven for several years. An examination of the mine maps showed that four rib lines, two on each side of the entry, were in such position that their break lines might be extended to form an X with the intersection over these headings, which apparently accounted for the sudden failure of the roof.

In one district studied, rooms were turned off both headings of each room-entry system and the pillars were recovered by the method known as the half advance and half retreat system. With this system, the rooms on one heading are driven as the entry advances and the pillars are extracted as the rooms are finished. When the entry is finished the rooms on the other heading are started at the inby end and are followed by pillar extraction. If all the pillars on the advancing side have not been extracted before the retreating line is started, conflicting stresses will be set up between the lines, often causing the loss of coal. This method of mining is not recommended, especially where the cover is heavy.

ANGLE OF BREAK LINE

All of the break lines described are at an angle with the room faces. The primary cause for this angle is the stepping of the rib lines to break the roof over the goaf instead of over the pillars, thereby relieving the roof over the pillars of undue stresses. The angles made by the break line and room faces vary from 20° to 60°; however, in 75 per cent of the mines the break lines were maintained on an angle of approximately 45° to the room faces.

The angle of the break line is a more important factor in controlling roof breaks than is generally realized and may be a determining factor in the success or failure of pillar recovery. Most of the roof strata contain two sets of joints perpendicular to the bedding planes, one set parallel to the strike of the strata and the other parallel to the dip. As the roof strata are largely concealed from direct observation except occasionally along outcrops or along break lines, little is known of the relationship that may exist between the cleats in the coal and joints in the roof or the effect of the

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roof joints in mining. In several instances, however, changes have been made in either the direction or angle of break lines which have resulted in improved roof conditions along the rib lines and indicate that pillar mining might be improved in other mines by a thorough study of the rock structure and its behavior in pillar extraction.

The following examples are illustrative of the results obtained along break lines at 45° to the room faces, but having bearings northeast-southwest and northwest-southeast.

Several rib lines were being worked in mine A, opened in the Pittsburgh coal under 450 feet of cover. About half of these lines had a general bearing northwest and southeast and the others were at 90° to these. All break lines made angles of approximately 45° with the face cleats in the coal. As the rib lines were developed it was found that the roof broke more freely along the northwest-southeast lines, and when breaks appeared on the surface their courses had approximately the same direction, even when over the break lines running northeast and southwest. To take advantage of the better roof breaks along the northwest-southeast rib lines, the management now plans to discontinue the rib lines at 90° to these as rapidly as possible, and in new development proposes to extract pillars along lines parallel to the planes of weakness in the roof.

In mine B, opened in the Pittsburgh coal under cover averaging 150 feet, the rib lines are maintained at an angle of approximately 45° to the room faces or face cleats in the coal and have a general direction northeast and southwest. Lying a few inches above the coal over a large part of the property is a bed of hard sandstone and sandy shale, 20 to 50 feet thick, having pronounced joints 15 to 25 feet apart, their course being approximately 45° to the face cleats and normal to that of the break line. These joints cause the roof to break in large blocks whose weight sometimes crushes the corners of pillars extending into the goaf. To prevent this, it was decided to strengthen the pillars along the break line rather than change its direction, as it was believed advisable to keep the break line normal to the joints rather than parallel to them. This was accomplished by splitting the pillars parallel with the rooms as shown in Figure 12, thus reducing the maximum offsets along the rib line from 100 feet to 50 feet and reducing the goaf area between steps proportionally. Since this method was adopted the corners of pillars have been crushed less and the roof appears to be less heavily stressed over the working places.

Mine C, opened in the Pittsburgh coal, has two rib lines, each under about 450 feet of cover. Both lines are over 2,000 feet long and cross the face cleats in the coal at an angle of approximately 45°; one line has a bearing roughly northeast and southwest and the other, 90° to the first, is northwest and southeast. The lowest stratum of the main roof over the mine consists of 35 to 40 feet of strong sandstone. This is separated from the coal bed over the northwest-southeast rib line by a few feet of shale and coal, but

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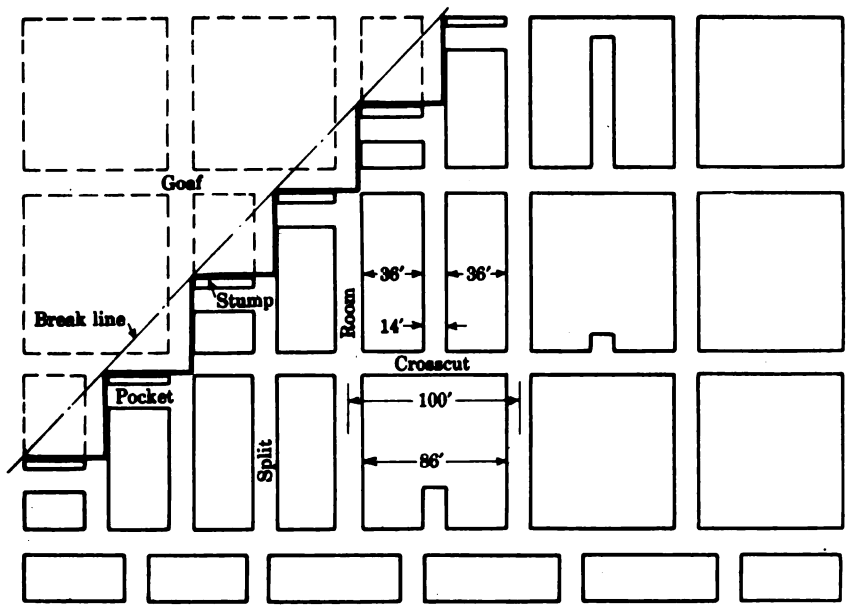

Figure 12.-Splitting room pillars to shorten steps along the rib line.

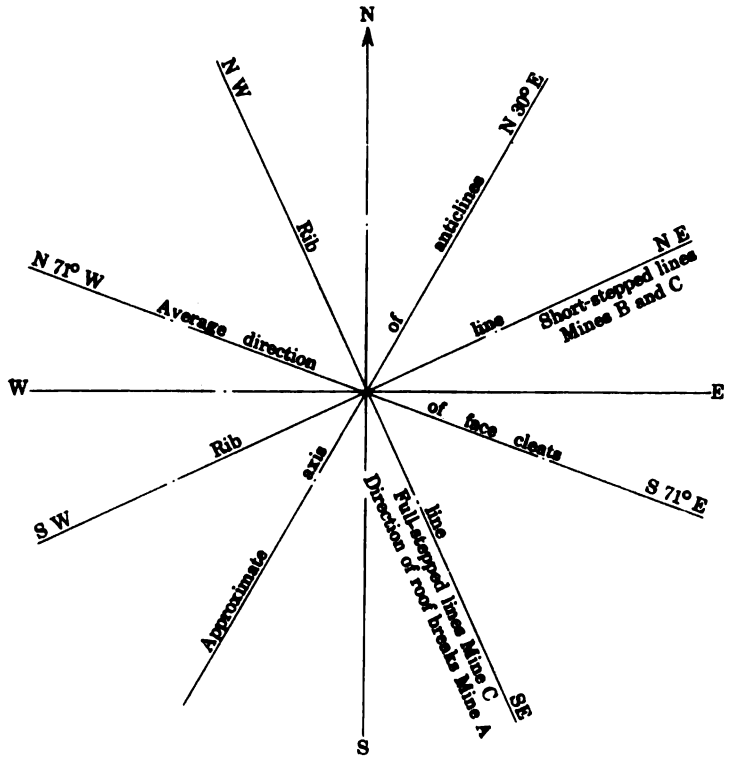

Figure 13.-Diagram showing direction of break lines with respect to cleat in coal and axis of anticlines.

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over the other rib line the sandstone is only a few inches above the coal. As the latter rib line was developed, much difficulty was experienced in breaking the roof. After several methods of extracting the pillars had been tried it was found that best results were obtained by shortening the steps along the rib line while maintaining the 45° break line. This was accomplished as in mine B, except that the pillars were mined by the open-end system instead of by pockets and stumps. No difficulty was experienced on the northwest-southeast rib line using the full block system, although splitting the pillars was tried.

The results of these observations in the three mines are shown in Figure 13. In this diagram the average bearing of the face cleats has been used, as has also been done to obtain the bearing of the anticlinal axes. As all of the rib lines were at 45° to the face cleats, they may be represented by the two lines intersecting at a right angle as shown. It will then be observed that the rib lines in mine A, along which the roof breaks more freely, have the same bearing as the full-stepped line in mine C and that the short-stepped line in C and the short-stepped lines in mine B have the same bearing. Mines A and B are in West Virginia and mine C in Pennsylvania. The two in West Virginia are about 10 miles apart, while mine C is over 40 miles from the former.

In the mines of one company operating in the Pittsburgh bed in Pennsylvania, it has been found that better roof breaks are obtained and less difficulty is experienced with the immediate roof in working places along the rib lines by maintaining the break lines at angles of 30° to the butt cleats, where places are driven on the butts, and 70° to the butt cleats where the places are driven on the faces. Little is known of the main roof structure in these mines, and it is not known whether the joints in the main roof or those in the coal are responsible for the choice of these angles.

In several mines having a strong, tough roof it is necessary to have the greatest possible support extended to the break line to prevent the strata from bending excessively over the working places. This may be done along a 45° break line by shortening the steps as in Figure 12, or it may be effected by changing the angle of the break line as in Figure 14 in which two full-stepped rib lines, one at 45° and the other at 30°, are compared. An examination of these show that the unsupported area A between the pillars when rooms are on 100-foot centers is 5,000 square feet along the 45° break line and 2,900 square feet along the 30° line; the distance c between points of support along the breakline B-B is 141 feet for the former and 116 feet for the latter; and the distances d from S-S, the line of maximum pillar support to the break line, are 71 feet and 50 feet, respectively.

This distance d is an important factor in breaking the roof and in maintaining a sound roof over the working places along the rib line. It has been stated that with the roof behaving as a cantilever, the bending moments and shear stresses are maximum along the points of support; as the maximum pillar

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support is along S-S and gradually diminishes to B-B, there will be a certain amount of bending over the pillars between S-S and B-B. Obviously, this will be greatest along B-B and will decrease to practically zero along S-S. It is therefore evident that as the distance d becomes shorter, the roof stresses will become more concentrated, facilitating the fracture of the roof and reducing the area over which the immediate roof will be disturbed.

Rooms and crosscuts have been shown on 100-foot centers; however, the same ratios will exist for other centers or where the pillars have been split, the only difference being that shortening the room centers reduces the proportion of solid coal along the rib lines and is equivalent to widening the rooms without changing the centers.

BEHAVIOR OF PILLARS ALONG RIB LINES

It has been shown that a certain amount of bending occurs over the pillars adjoining the rib line. The extent to which the roof bends is controlled by the distance between the break line and the line of support and the resistance afforded by the coal pillars. The first factor may be controlled by methods already described; control of the second depends on the structure and strength of the coal.

The vertical joints or cleats commonly found in the coals of bituminous and semibituminous rank are probably the most important structural features to be considered. These joints, although sometimes more or less obscure, generally occur in two sets intersecting at approximately 90°. The longer and more pronounced of these joints are known as the face cleats, while the others, which are shorter and less defined, are known as the butt or end cleats.

As a rule, when a pillar is subjected to excessive load, cracks develop along the face cleats and pronounced spalling of the coal occurs along the rib parallel to these joints. The depth to which the pillars are affected depends on the load and the degree of development of the joints. This is particularly noticeable in pillar work where the pocket-and-stump method of extraction is used. Referring to Figure 2 A, which is representative of this method, it will be noted that in the stump along the pocket turned off the room the face cleats are parallel to the longer sides, and in the stump adjoining the pocket driven off the crosscut the face cleats are parallel to the ends. After observing the behavior of coal in both types of stumps in both the Pittsburgh and Sewickley coal beds, the writer is convinced that in two congruous rectangular pillars, one with the face cleats parallel to the longer sides and in the other parallel to the shorter sides, the former will offer less resistance to roof pressure than the latter and this difference will become greater as the length of the pillars increases with respect to the breadth.

The extent to which the arrangement of the cleats in stumps affects the main roof is not definitely known, provided that a straight break line is maintained; however, stumps in which the face cleats are parallel to the shorter sides are known frequently to break the immediate roof over pockets

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driven in pillars in the Pittsburgh coal. In many mines this effect has been overcome by making such stumps narrower than those in which the face cleats are parallel to the longer sides. In most mines in the Pittsburgh coal it is possible to leave stumps 12 to 15 feet wide where the face cleats are parallel to the longer sides, while the stumps at right angles to these generally must be kept less than 6 feet wide in order not to break the immediate roof over the face pockets. In a few mines the difficulty attendant upon leaving stumps along the face pockets is eliminated by driving only butt pockets, along which it is possible to leave stumps two machine-cuts thick; however, this method is not always advisable, as it is sometimes necessary to keep the pillar blocks as nearly square as possible. One company has managed this in a most commendable manner by driving butt pockets off the rooms, leaving stumps 12 feet wide, and by driving face places on the open end, leaving a thin curtain of coal not to exceed 2 feet thick to prevent rock in the goaf from sliding into the working place. After each face place is driven across the end of a pillar, two slabbing cuts are made from the pillar, as in Figure 15. This method permits the removal of as much coal from the end of the pillar as would be taken if mined by pockets, leaving 12-foot stumps.

The poorly defined cleats in the Pocahontas No. 3 coal apparently have no effect on the method of mining; however, the friable nature and columnar structure of this coal causes it to behave along all ribs much as does the harder Pittsburgh coal parallel to the face cleats. At the vertex of converging rib lines in one mine where the coal was 7 feet thick and under 500 feet of cover, the coal along the ribs was badly crushed and spalling from the sides, but when the pockets were driven to a depth of 6 feet in the pillar no visible evidence of crushing was found. This would indicate that with the pocket-and-stump method of pillar extraction, stumps 12 to 14 feet wide might be used successfully. This assumption was borne out in three mines where 12-foot stumps were the standard. In another mine the stumps were 6 to 8 feet thick and were apparently causing no difficulty, although they were sometimes crushed more than when wider. In one mine the pillars were removed on the open end with fair results. In this mine the recovery was high, but the working places were in worse condition generally than those found in an adjoining mine having the same management but where the pocket-and-stump method was used.

MAINTAINING RIB ALINEMENT

After establishing a rib line every effort must be made to maintain a straight break line. If pillars are recovered as the rooms are finished, adequate development must be provided to preclude delays along the rib line while waiting for rooms to be finished. Conversely, if all rooms have been driven before commencing pillar recovery, every effort should be made to obviate delays due to reconditioning the rooms for pillar mining. Falls and water are causes of delay that may be avoided or mitigated by regular inspection and by keeping necessary supplies on hand. Lack of adequate supplies is a common cause of delay in many mines. Every effort should be made to anticipate the operating necessities.

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Competent supervision is essential in all underground work and it becomes imperative in pillar extraction if best results are to be obtained. As an aid to the pillar bosses, guide lines parallel to the break line may be drawn on the maps furnished them. The points on the pillars where these lines intersect the ribs should then be marked with white paint and given a number or letter corresponding to that of the line on the blueprint. These lines should be spaced to represent not more than 50 feet and if possible should be spaced to represent the distance that the pillar is shortened by each successive pocket-and-stump or open-end cut. With such guides there should be no excuse for irregularities in the rib line, provided that it was not delayed by lack of development, extensive falls, or water.

Several mines have adopted a plan known as the "clean-up" system that makes possible a more uniform rate of advance or retreat. This system embodies the principle of providing each loader with only so much coal for loading as he can dispose of during the shift, along with his other duties. In one mine opened in the Pittsburgh bed each loader averaged 19.3 tons per 8-hour shift in addition to drilling three holes, setting one permanent post, and advancing his track. No draw slate is handled, as a stratum of coal is left up to support it. With such a system, all working places are cleaned up at the end of a shift and are ready to be cut on the night shift, so that the foreman is able to estimate accurately the rate of advance or retreat of each place.

COMMON CAUSES OF FAILURE IN PILLAR MINING

Pillar recovery has been unsuccessful in some districts or in individual mines, giving rise to the belief that pillar extraction is impossible in those places. This may be true in a few instances, as in thin coal beds overlain with a tough roof that bends to the floor without breaking or where fracturing the roof would cause serious inflows of water. Usually, however, disappointing results in pillar extraction may be attributed to the failure of the management to consider carefully all of the factors that affect pillar mining. In one district where several unsuccessful attempts have been made to recover pillars, the failure may be attributed to the following causes: (1) Leaving room pillars too small; (2) making rib lines too short; (3) improper choice of pillaring method; and (4) incomplete recovery.

If pillars are to be recovered, they should be at least as wide as the rooms and wider if the cover is heavy. It is interesting to note that in those districts where pillar recovery is most systematic, the ratio of the room widths to the pillars varies from 1:5 to 1:9 and averages 1:7; whereas in the districts where pillar extraction is considered impossible, the ratios are from 1:0.4 to 1:0.5.

The length of the pillar line as a factor in successfully breaking the roof has been fully discussed, but it is well to add that more pillar mining has failed because the rib lines were too short than because they were too long.

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Every effort should be made to find the pillaring method most suitable to conditions in the mine. In the mines where best results were attained in recovering pillars, the pocket-and-stump or the open-end method or a combination of the two methods was used, whereas in those mines where pillaring was considered a failure, the slabbing method was used most frequently. If the rooms are driven on the face cleats and the pillars are too narrow for both butt and face places to be driven, it is believed that butt pockets leaving a stump 6 to 7 feet thick will be most satisfactory.

Complete recovery or the removal of all standing pillars that could record subsidence is essential where the coal is overlain with a strong roof. This is considered of such importance by some companies that every pillar must be removed even if abnormal conditions occasionally make extraction of an individual pillar cost more than may be realized from the coal. This practice is followed to prevent squeezes which might prove more expensive than recovery of single pillars.

In the districts where pillar recovery is practiced, the results sometimes are far from satisfactory. Occasionally, these effects may be attributed to inherently bad roof which will not respond in any marked degree to the mining methods now practiced, but more often the cause may be traced to indifference or inexperience on the part of the management. The more common causes of incomplete success in pillar extraction in the districts where pillar mining is generally practiced are: (1) Irregular alinement of rib lines; (2) conflicting break lines; (3) delay in recovery of pillars; (4) failure to observe the behavior of the roof; (5) improper method of extracting pillars; and (6) incomplete recovery.

Irregular alinement is probably responsible for most of the difficulty experienced in pillar extraction. Every effort should be made by the management to maintain a straight break line. In addition to the methods previously described for maintaining rib alinement, some companies employ pillar inspectors or fall bosses whose principal duty is to see that the break line is kept straight. Whenever possible, the single form of rib line should be used and every effort should be made to avoid the converging V-form.

Conflicting break lines often cause the roof to break over working places, even in solid coal. This generally can be avoided by careful planning and by maintaining a minimum number of rib lines.

Rooms should be driven primarily to develop pillars for recovery rather than as a principal source of output. Overdevelopment in the form of rooms is due generally to the management's being inexperienced in pillar mining and expecting to obtain a large output at low production cost. Rooms where pillars are extracted should be driven just far enough in advance of pillar mining to preclude the possibility of delay along the rib line.

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The angle of break in the roof should be determined as early as possible and the break lines should parallel the natural fracture line in the roof. Where this is impracticable, the length of step along the rib line should be regulated to provide the best possible breaks.

The same method of extracting pillars will not be successful in all mines and the management should lose no time in determining the method best adapted to the local conditions. In general, some form of the pocket-and-stump method, open-end method, or combination of the two should be used. Observations in the mines studied seem to indicate that where pillars are mined on the butt cleat the pocket-and-stump method, leaving a stump 7 to 15 feet wide, is most successful; but when places are driven on the face cleats the open-end method has proved best. In a soft coal without pronounced cleat the pocket-and-stump method apparently is better, but if the coal is hard and does not spall along the rib, the open-end method might prove better.

CONCLUSION

The foregoing discussion deals with engineering practices in mine development. Particular stress is laid on the importance of pillar recovery and on conservation and economy, but the predominating thought has been to present the methods which appear to give promise of greater safety against personal injury from falls of roof or coal.

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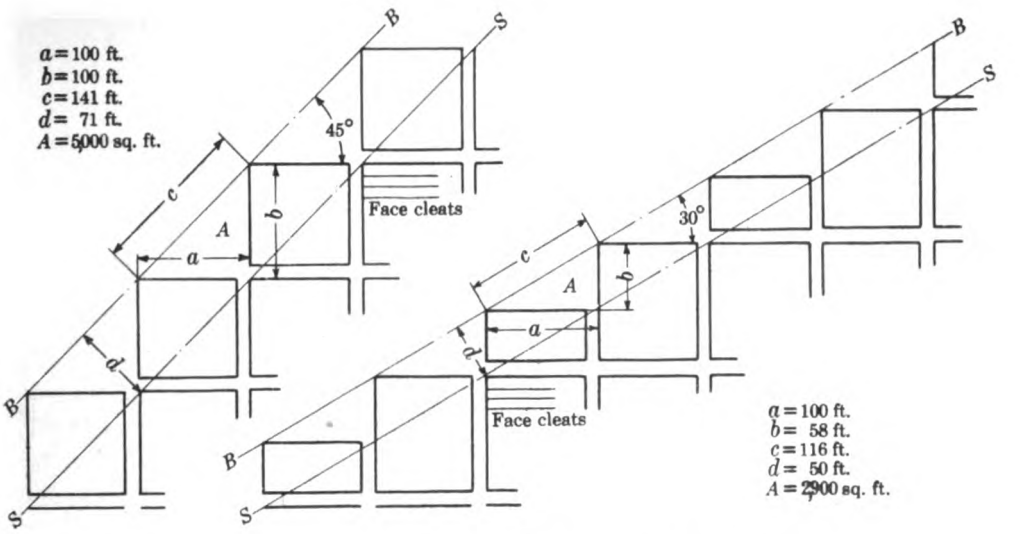

Figure 14.-Comparison of pillar support along 45° and 30° break lines.

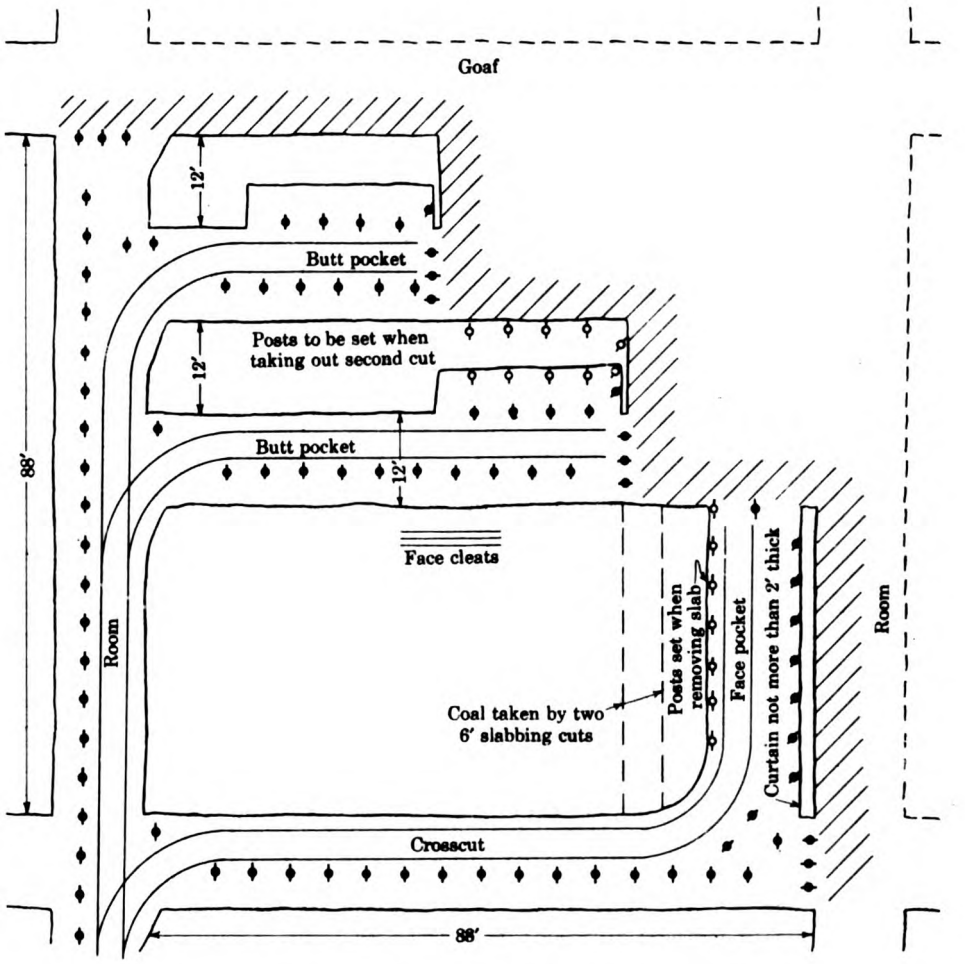

Figure 15.-Mining pillars by a combination of pocket-and-stump and open-end methods.

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